

Self-consistent simulations of particle beam/plasma interaction with its environment

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**Heavy Ion Fusion Science Virtual National Laboratory
Lawrence Berkeley National Laboratory**

DOE OFES Theory Seminar Series
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Outline

Context

Simulation tools

Benchmarking against experiments

Application to high energy physics

Summary

Context

— The Heavy Ion Fusion Science Virtual National Laboratory —



Today's HIFS program is directed at beam & Warm Dense Matter physics in the near term, and IFE in the longer term

Heavy Ion Fusion Science experiments:

The physics of compressing beams in space and time

- Drift compression and final focus
- High brightness beam preservation
 - Electron cloud, beam halo, non-linear processes

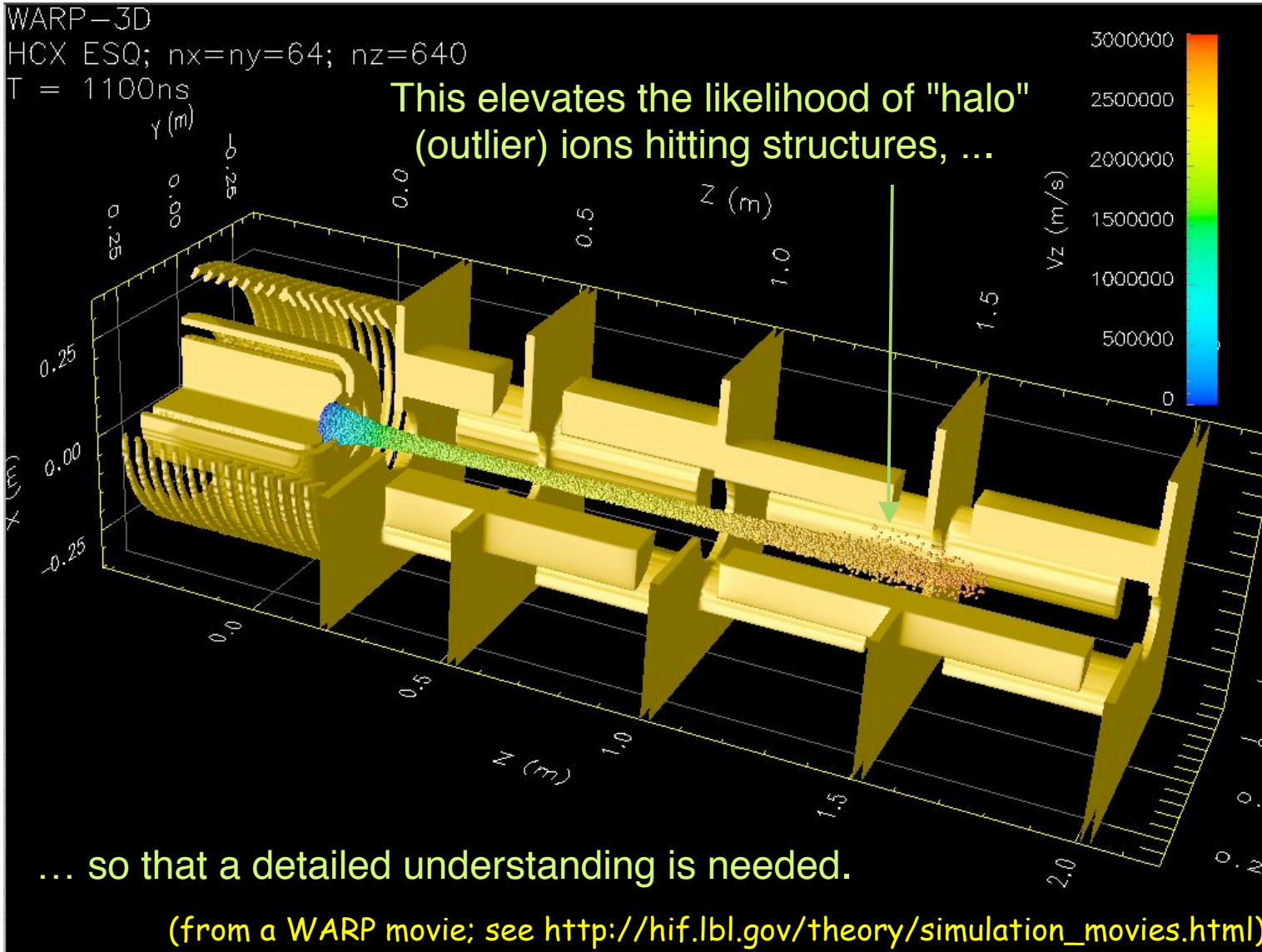
Warm Dense Matter (WDM) experiments

- Equation of state
- Two-phase regime and droplet formation
- Insulator and metals at WDM conditions

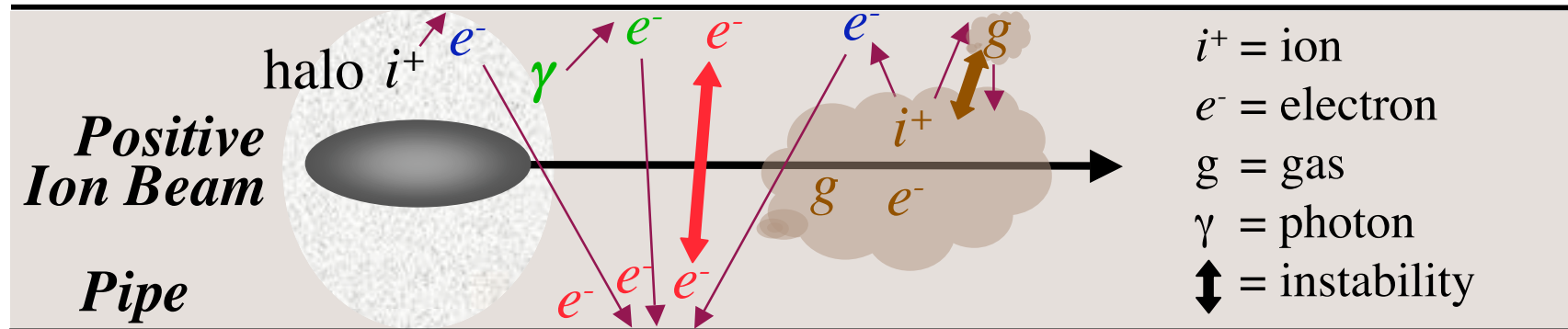
Hydrodynamics experiments relevant to HIF targets

- Hydrodynamic stability, volumetric ion energy deposition, and Rayleigh-Taylor mitigation techniques

It is highly desirable to minimize the space between the beam and the accelerating structure.



Sources of electron clouds



Primary:

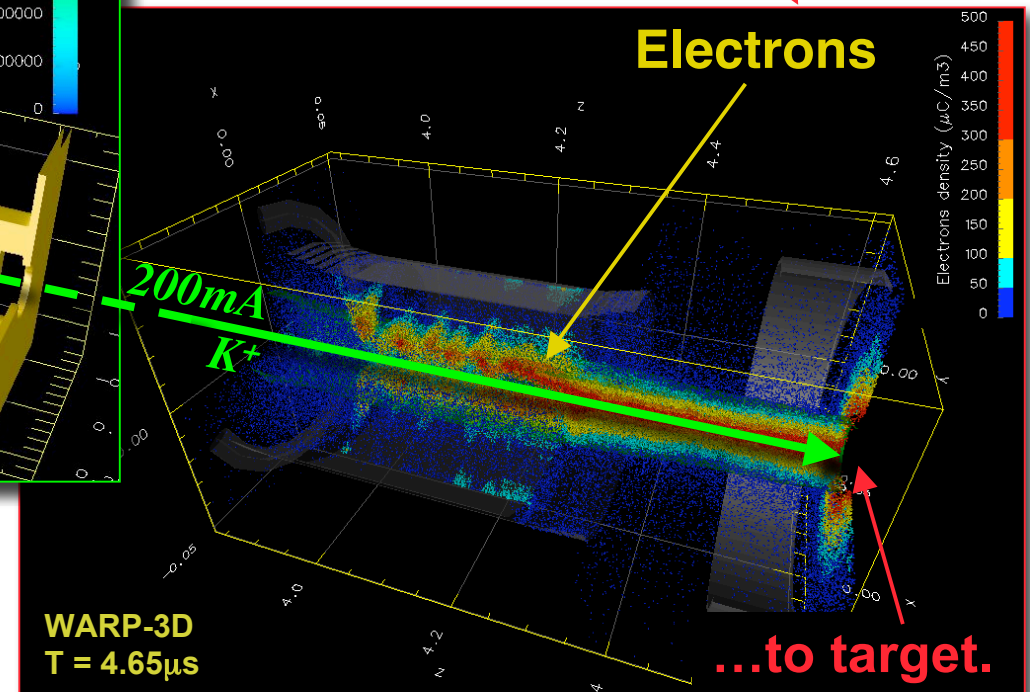
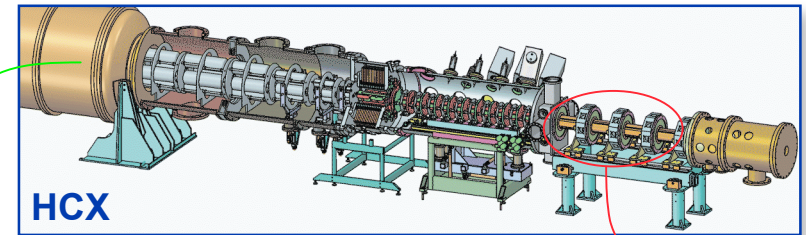
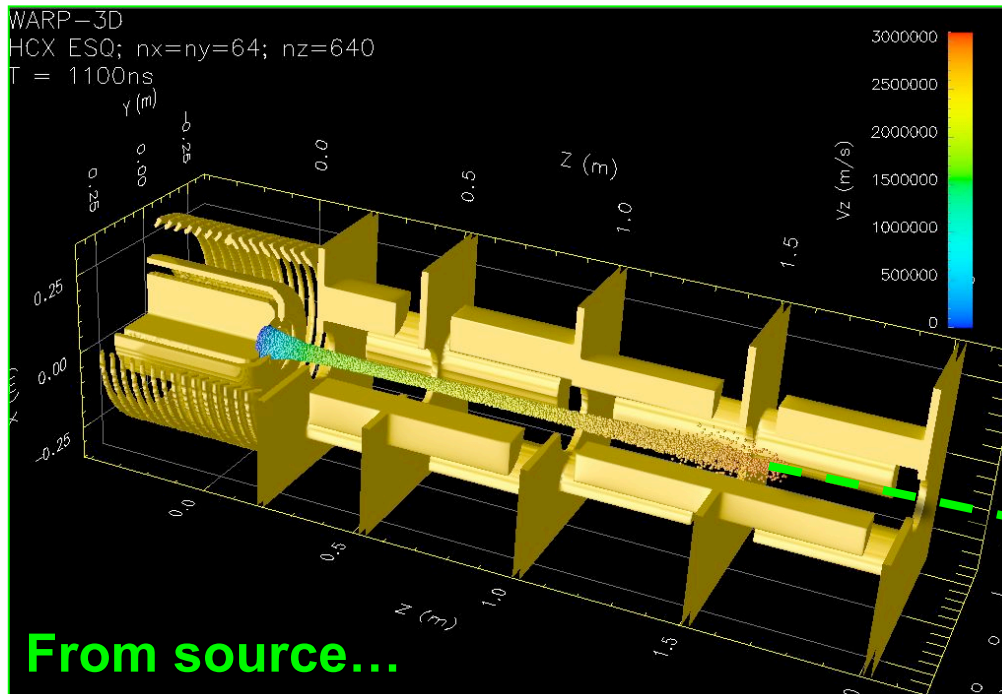
- **Ionization of**
 - background gas
 - desorbed gas
- **ion induced emission from**
 - expelled ions hitting vacuum wall
 - beam halo scraping
- **photo-emission from synchrotron radiation (HEP)**

Secondary:

- **secondary emission from electron-wall collisions**

Simulation goal - predictive capability

Source-through-target **self-consistent** time-dependent 3-D simulations of beam, electrons and gas with self-field + external field (dipole, quadrupole, ...).



Simulation tools

WARP is our main tool

3-D accelerator PIC code

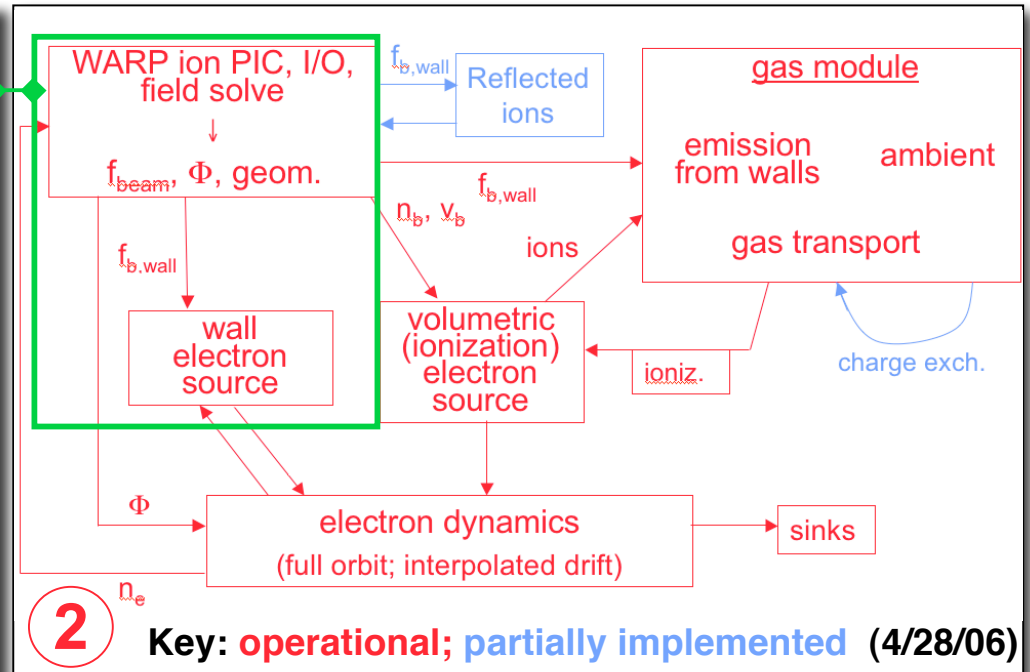
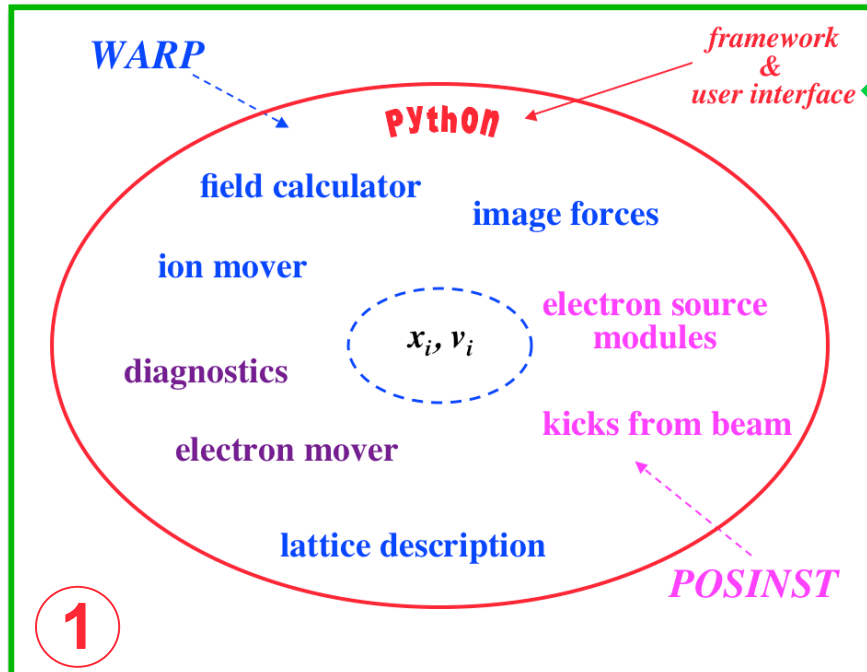
- Geometry: **3D**, (x,y), or (r,z)
- Field solvers: FFT, capacity matrix, multigrid
- **Boundaries:** “cut-cell” --- no restriction to “Legos”
- Bends: “warped” coordinates; no “reference orbit”
- Lattice: general; takes MAD input
 - solenoids, dipoles, quads, sextupoles, ...
 - arbitrary fields, acceleration
- Diagnostics: Extensive snapshots and histories
- **Parallel:** MPI
- **Python and Fortran:** “steerable,” input decks are programs

WARP-POSINST has unique features

merge of WARP & POSINST

+

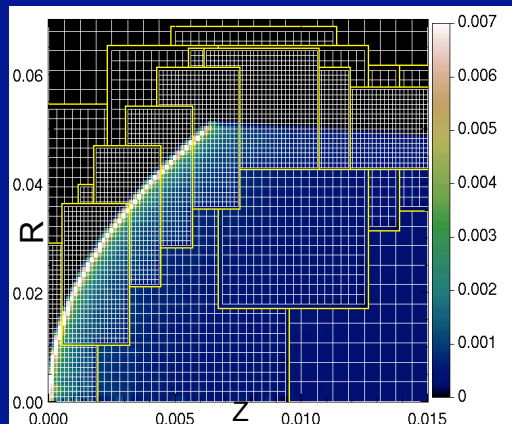
new e-/gas modules



+ Adaptive Mesh Refinement

concentrates resolution only where it is needed

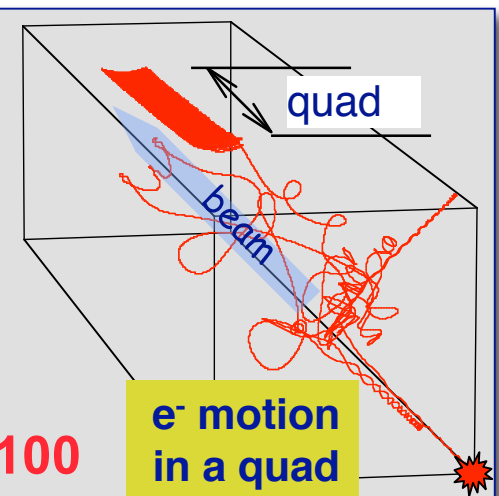
3 Speed-up $\times 10^{-10^4}$



+ Novel e⁻ mover

Allows large time step greater than cyclotron period with smooth transition from magnetized to non-magnetized regions

4 Speed-up $\times 10-100$



POSINST provides advanced SEY model.

Monte-Carlo generation of electrons with energy and angular dependence.

Three components of emitted electrons:

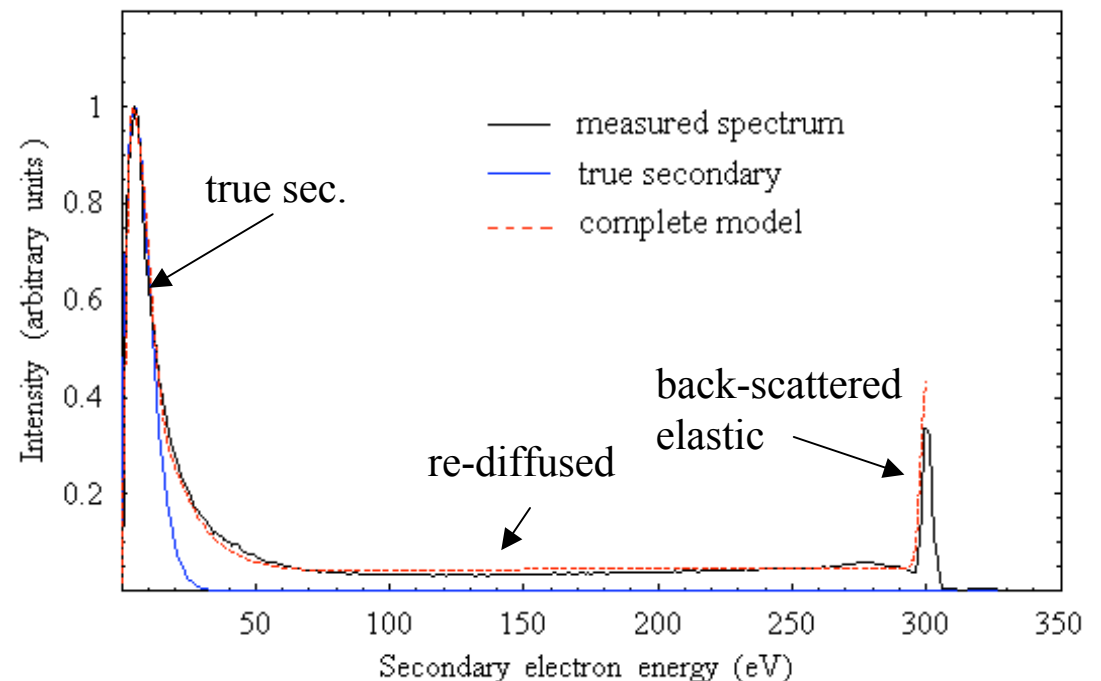
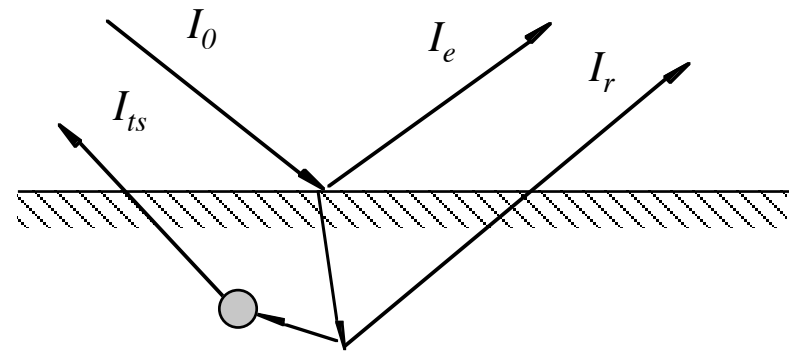
backscattered: $\delta_e = \frac{I_e}{I_0}$,

rediffused: $\delta_r = \frac{I_r}{I_0}$,

true secondaries: $\delta_{ts} = \frac{I_{ts}}{I_0}$

Phenomenological model:

- based as much as possible on data for δ and $d\delta/dE$
- not unique (use simplest assumptions whenever data is not available)
- many adjustable parameters, fixed by fitting δ and $d\delta/dE$ to data

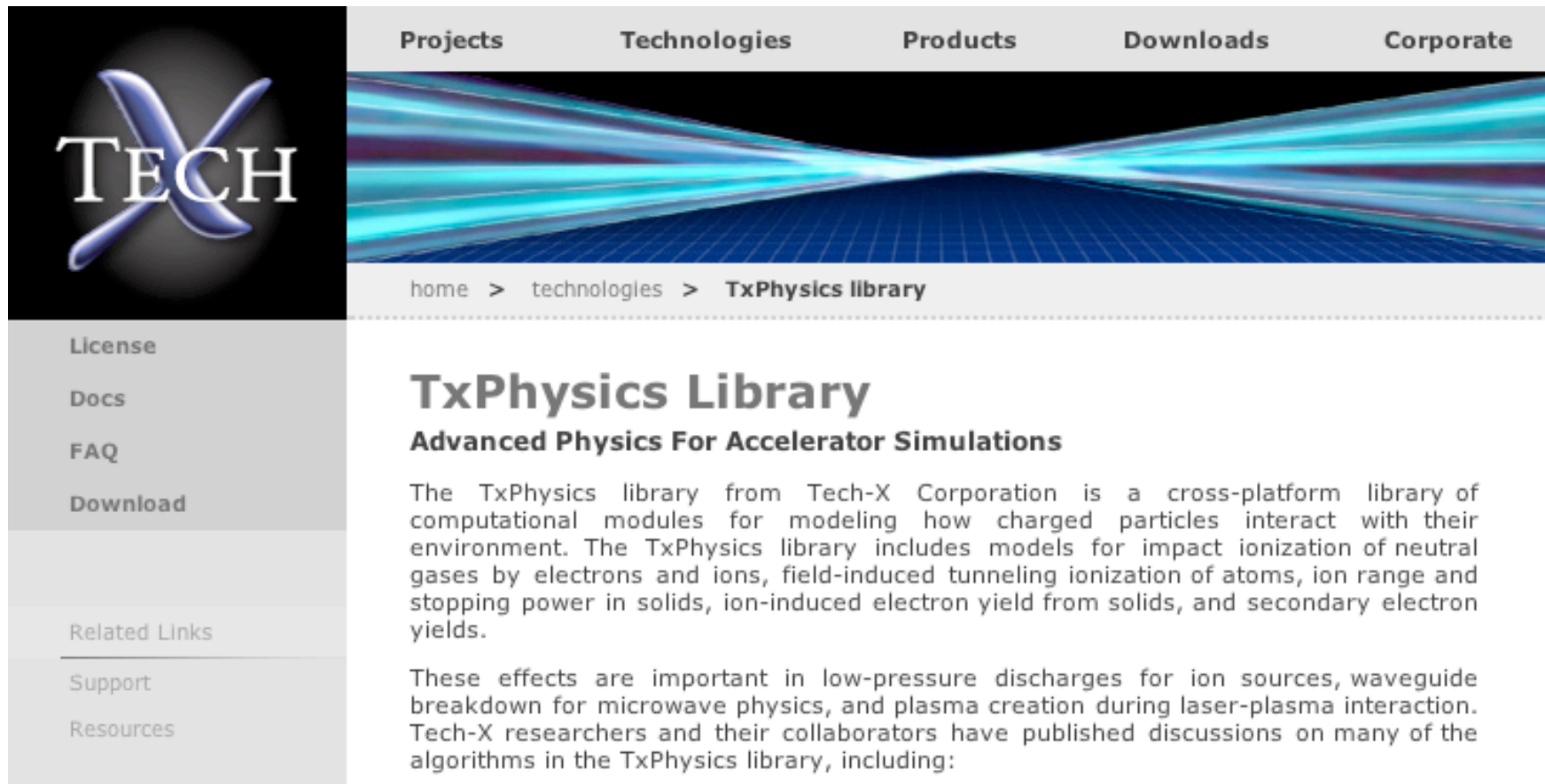


The Heavy Ion Fusion Science Virtual National Laboratory



We have benefited greatly from collaborations

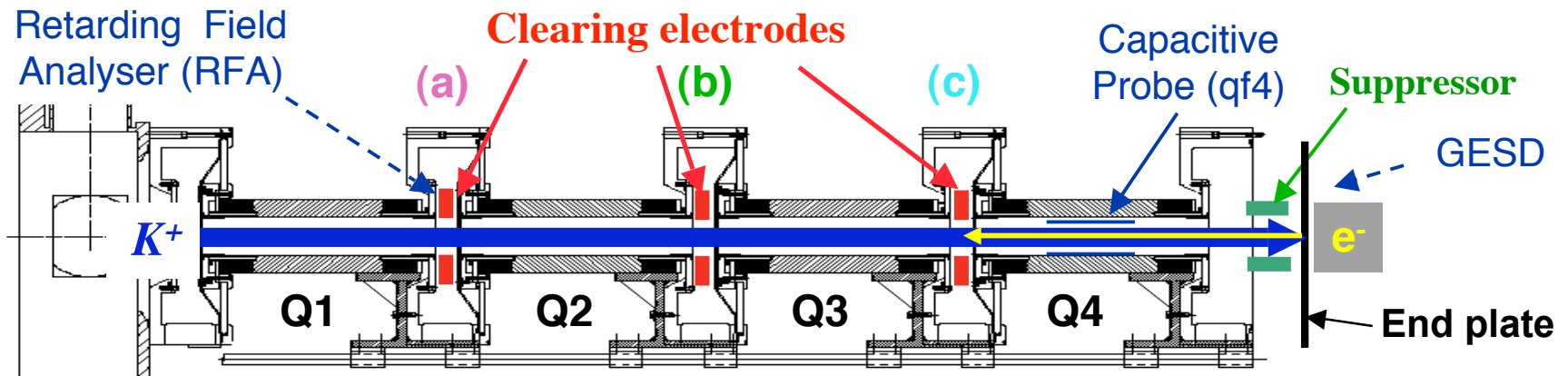
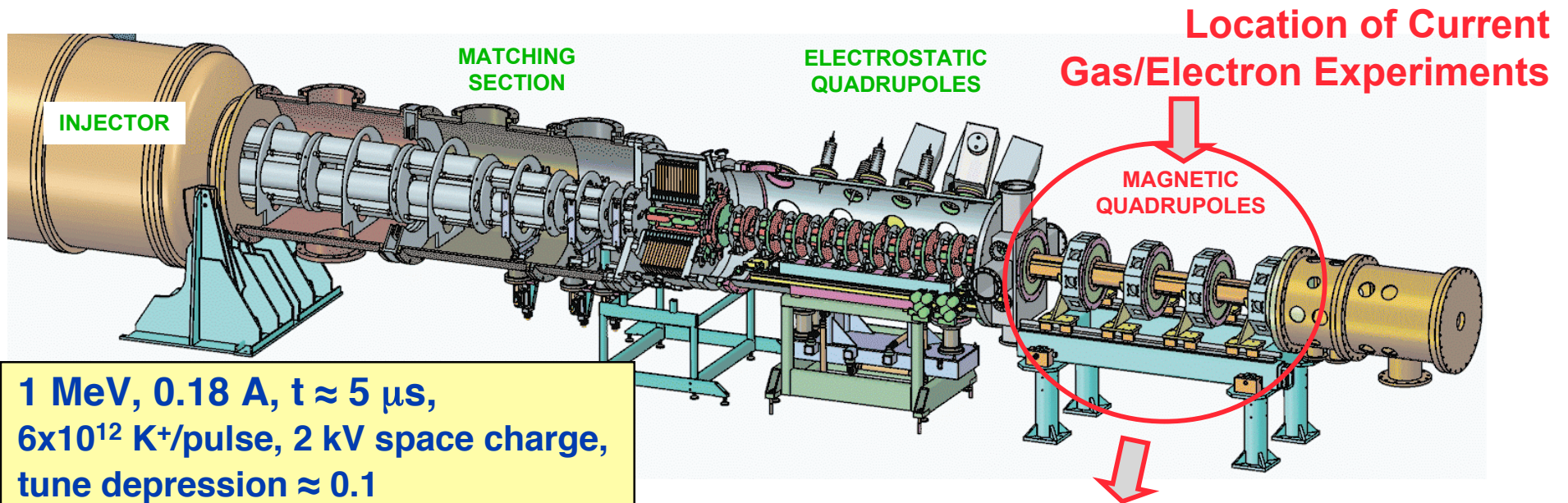
- ion-induced electron emission and cross-sections from the TxPhysics* module from Tech-X corporation (<http://www.txcorp.com/technologies/TxPhysics>),



- ion-induced neutral emission developed by J. Verboncoeur (UC-Berkeley).

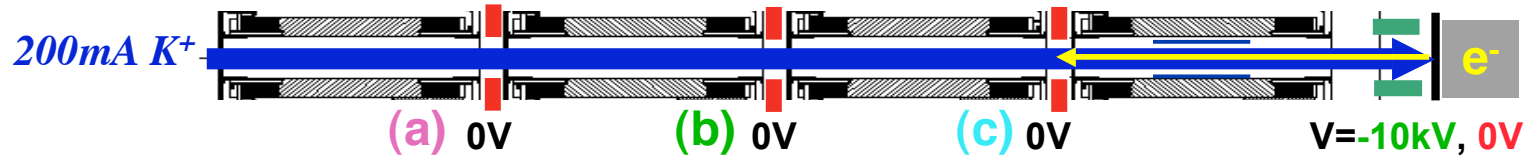
Benchmarking against experiments

Benchmarked against dedicated experiment on HCX



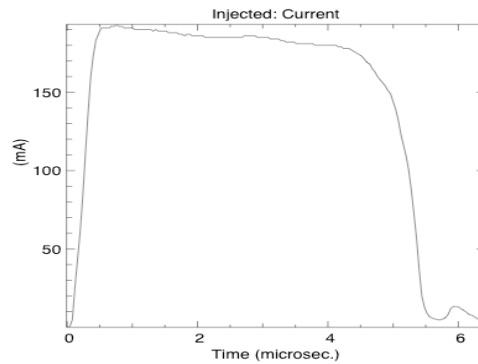
Short experiment \Rightarrow need to deliberately amplify electron effects:
let beam hit end-plate to generate copious electrons which propagate upstream.

Comparison sim/exp: clearing electrodes and e⁻ supp. on/off

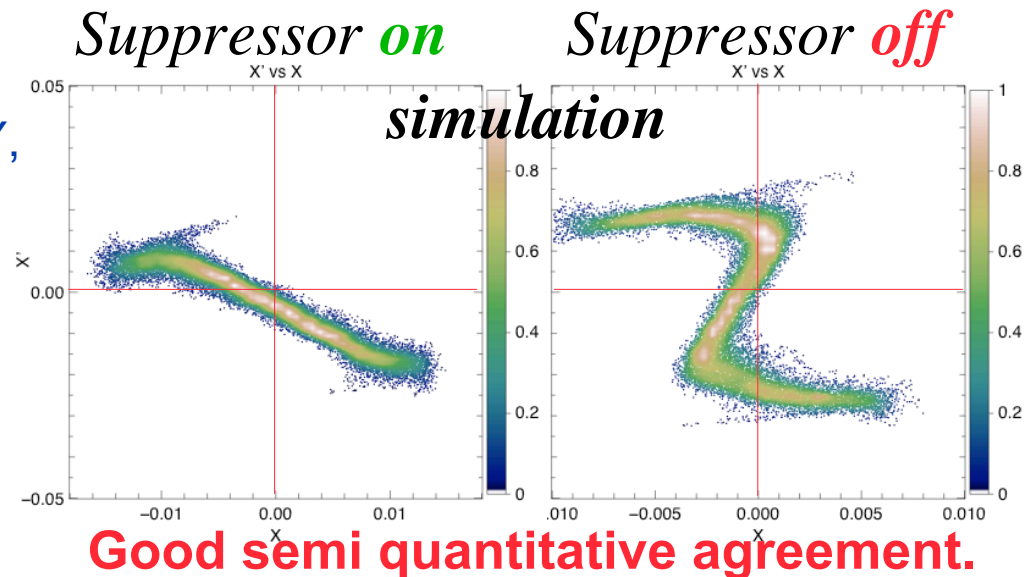
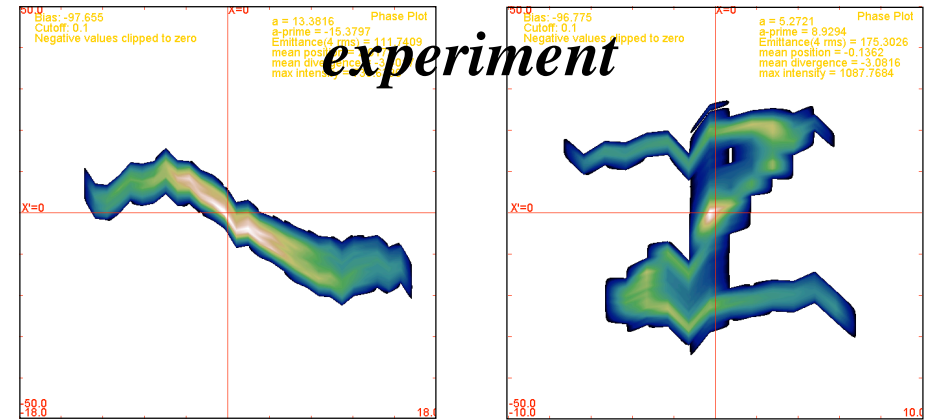
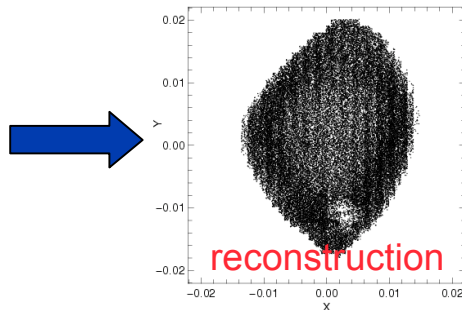
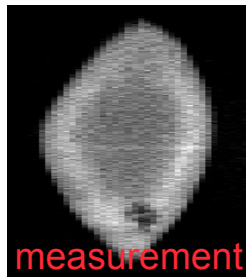


Time-dependent beam loading in WARP
from moments history from HCX data:

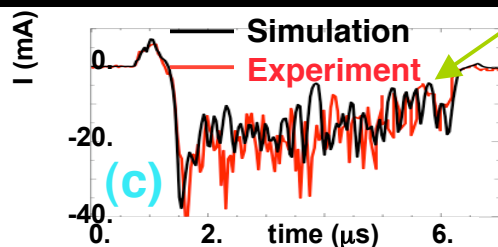
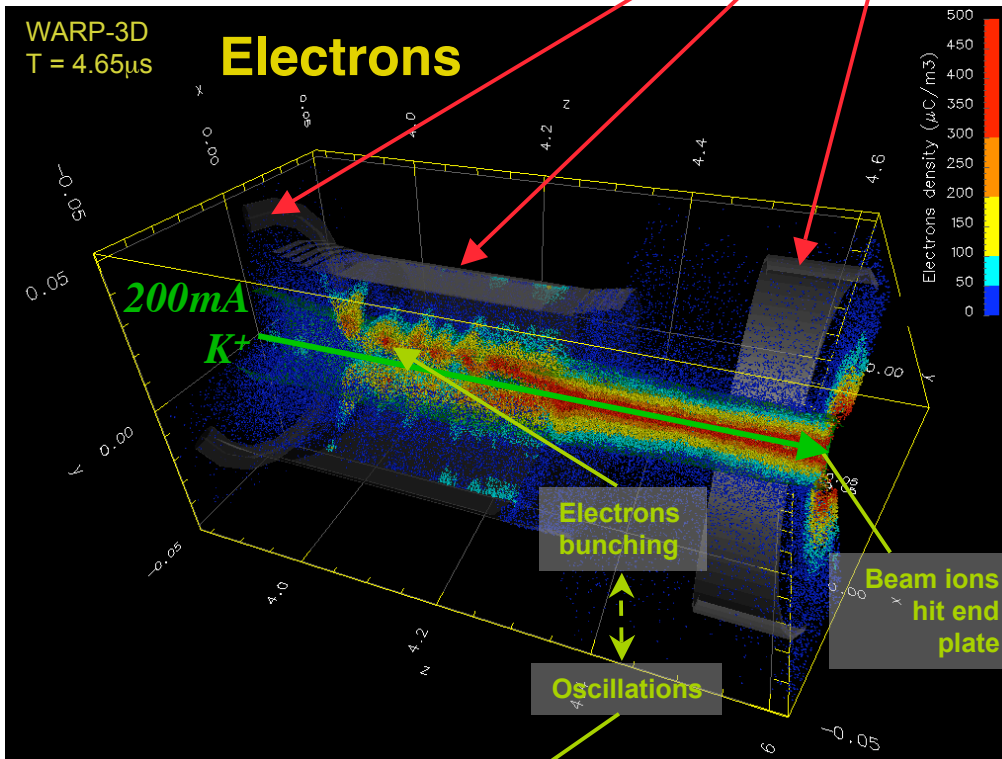
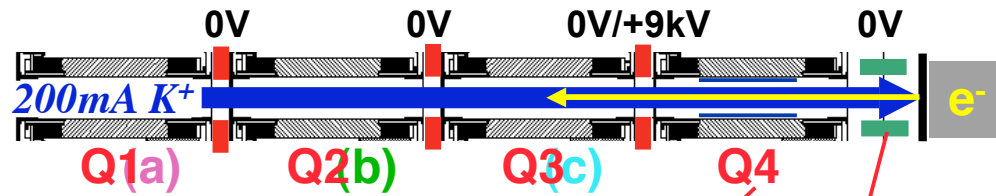
- current



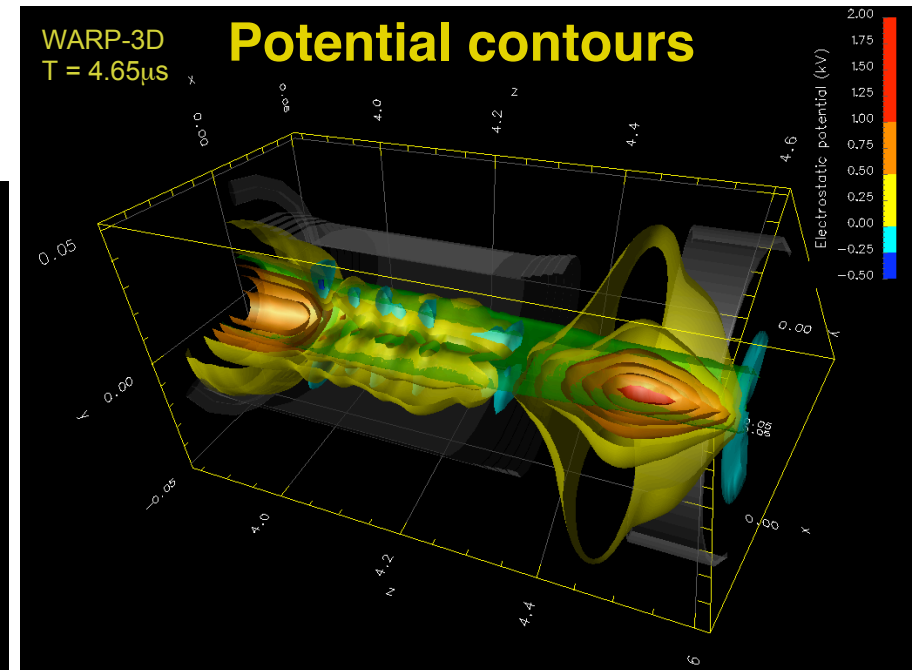
- energy
- **reconstructed** distribution from XY, XX', YY' slit-plate measurements



Detailed exploration of dynamics of electrons in quadrupole

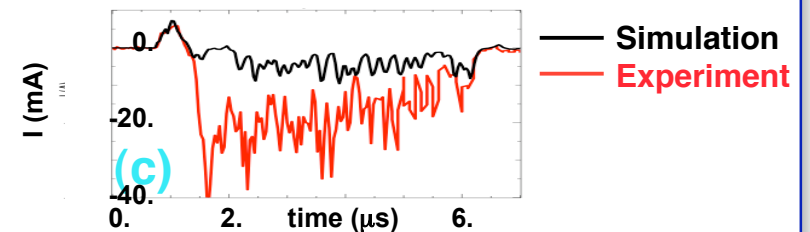


~6 MHz signal in (c) in simulation AND experiment



1. Importance of secondaries

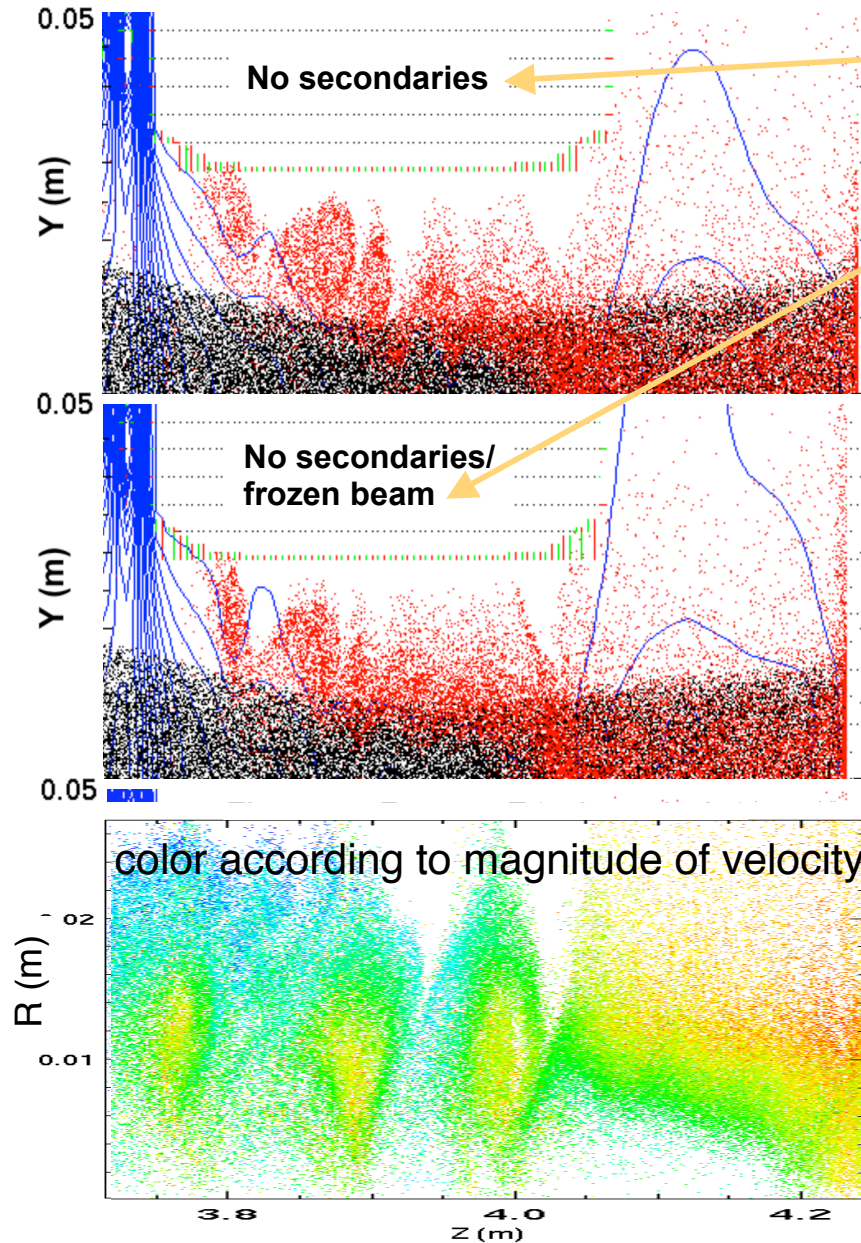
- if secondary electron emission turned off:



2. run time ~3 days

- without new electron mover and MR, run time would be ~1-2 months!

Quest - nature of oscillations



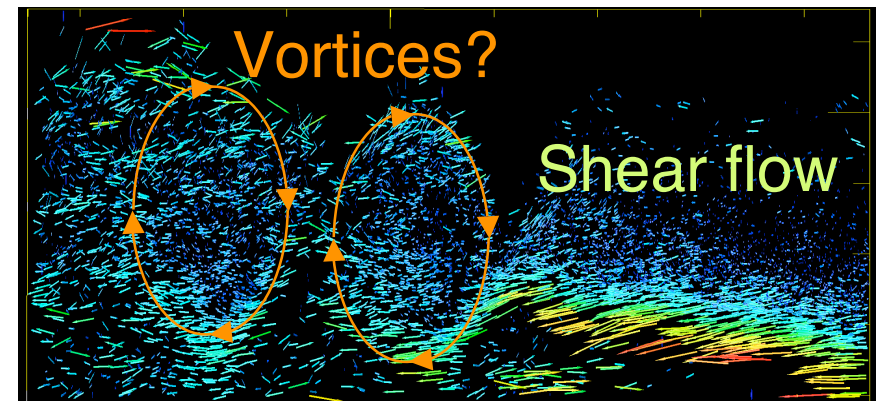
Progressively removes possible mechanisms

Not ion-electron two stream

Other mechanisms:

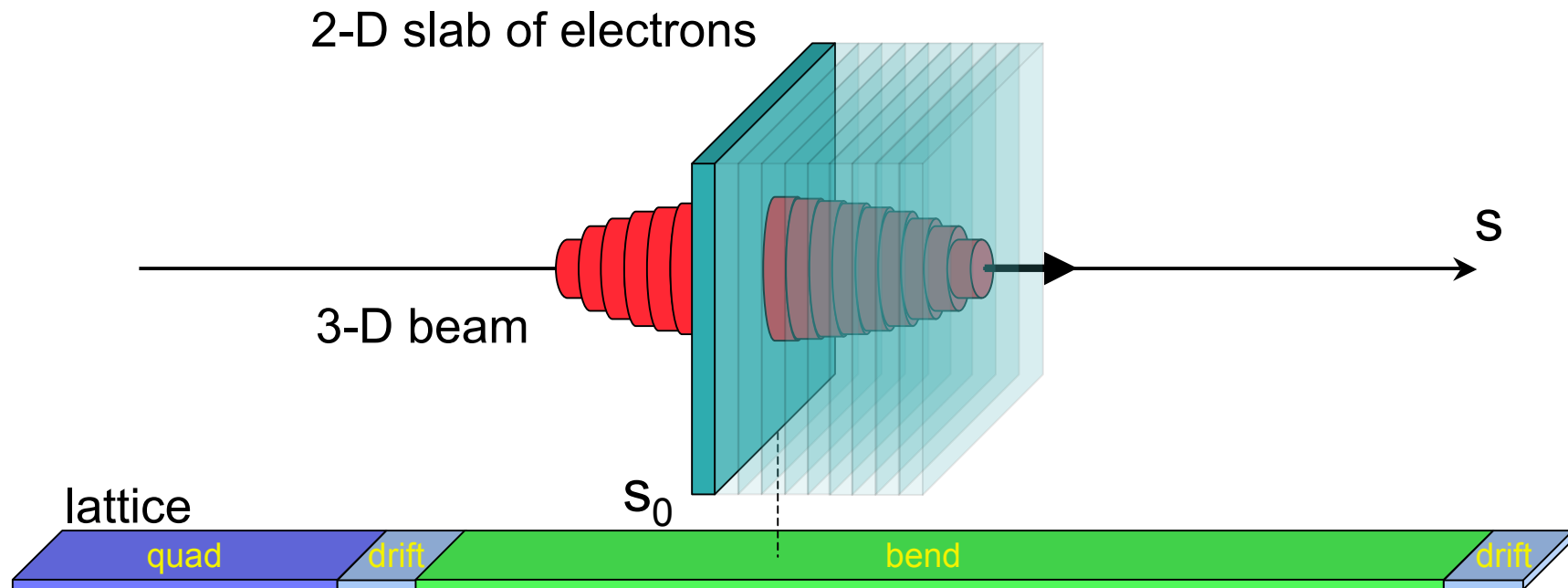
- Virtual cathode oscillations
- δ -Density \Rightarrow δ -potential, feedbacks to drift velocity
- Kelvin Helmholtz/Diocotron (plausible, shear in drift velocities)

Fluid velocity vectors
(length and color according to magnitude)



Application to high energy physics

HEP e-cloud work currently uses “quasi-static” approximation



A 2-D slab of electrons (macroparticles) is stepped backward (with small time steps) through the beam field and 2-D electron fields are stacked in a 3-D array, that is used to push the 3-D beam ions (with large time steps) using maps (as in HEADTAIL-CERN) or Leap-Frog (as in QUICKPIC-UCLA), allowing direct comparison.

Quasi-static mode (QSM) has been added to WARP

Rationale

- we had the building blocks
- we need to reproduce HEP codes results for meaningful comparisons

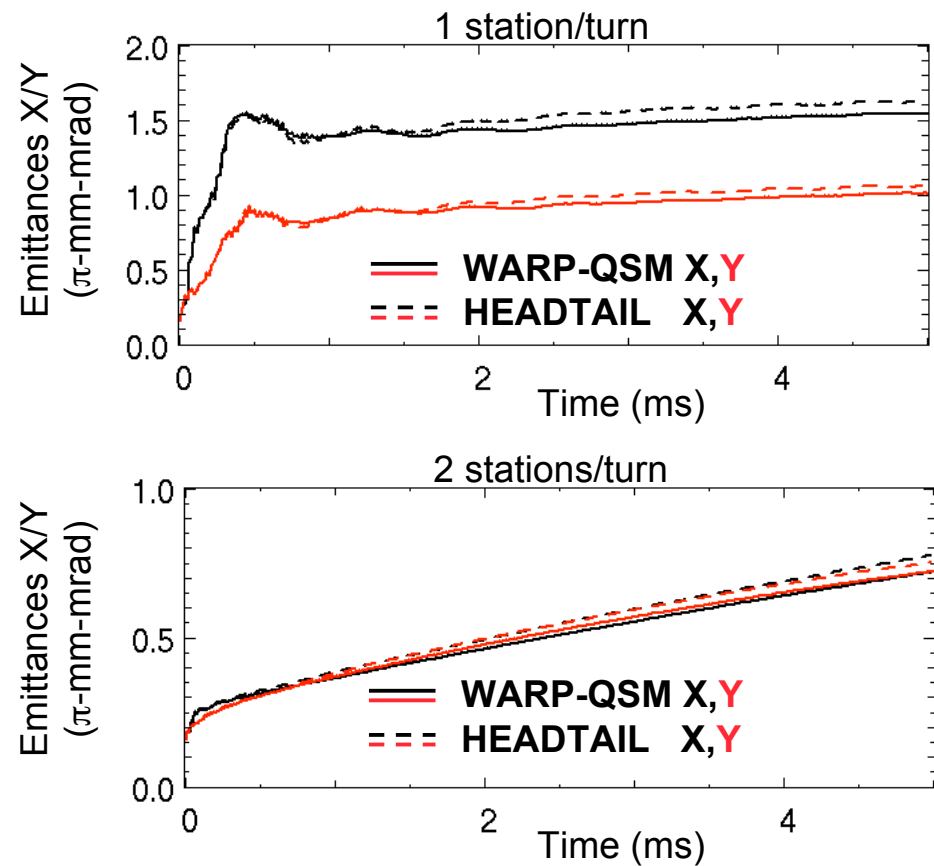
Comparison WARP-QSM/HEADTAIL on CERN benchmark

Proposed Model for Instability Simulations

round bunch in a round pipe: $1e11$ protons
uniform electron cloud with density $1e12 \text{ m}^{-3}$
each bunch passage starts with a uniform cloud
chamber radius 2 cm
uniform transverse focusing for beam propagation
zero chromaticity, zero energy spread
no synchrotron motion
energy 20 GeV
beta function 100 m
ring circumference 5 km
betatron tunes 26.19, 26.24
rms transverse beam sizes 2 mm (Gaussian profile)
rms bunch length 30 cm (Gaussian profile, truncated at $\pm 2 \sigma_z$)
no magnetic field for electron motion
elastic reflection of electrons when they hit the wall

NEW: with open and/or conducting boundary conditions (please specify boundary assumed), with 1 and/or several interaction points per turn or continuous interaction (please specify)

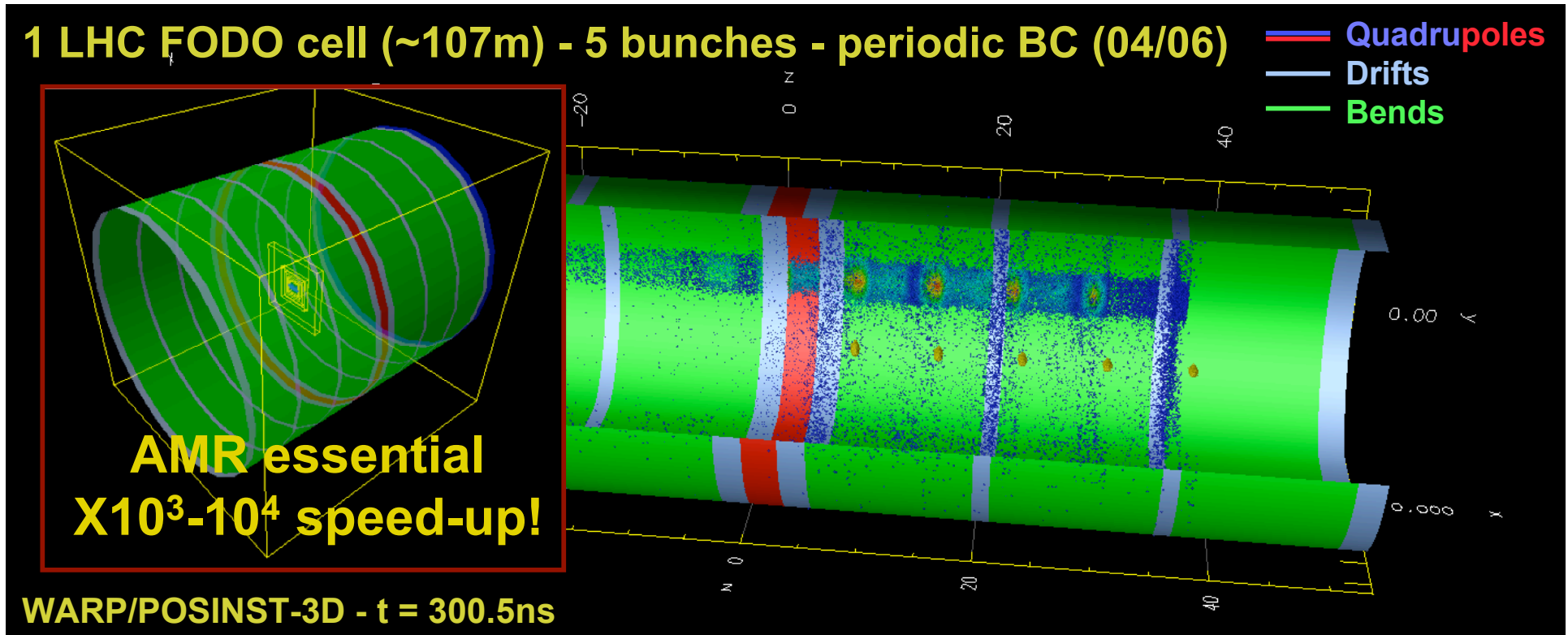
result: plot of x&y emittances vs time



WARP/POSINST applied to High-Energy Physics

- LARP funding: simulation of e-cloud in LHC

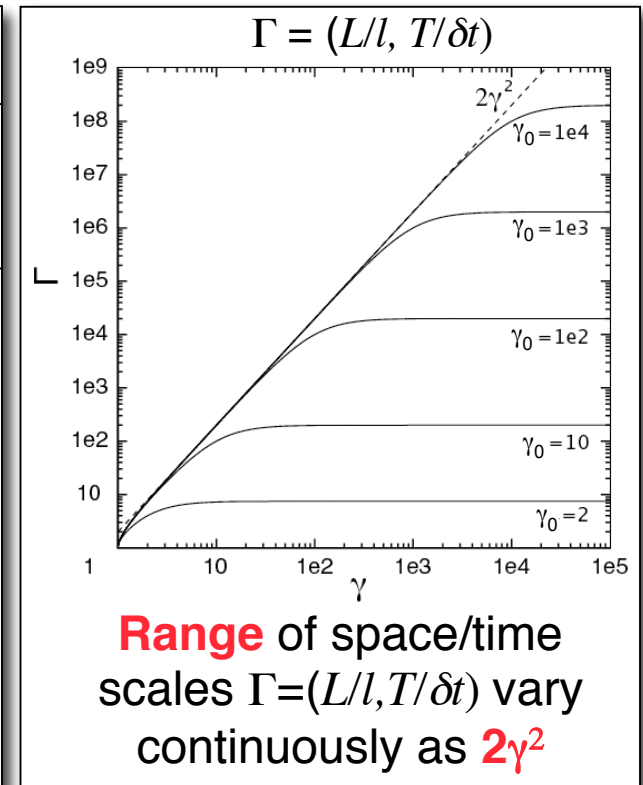
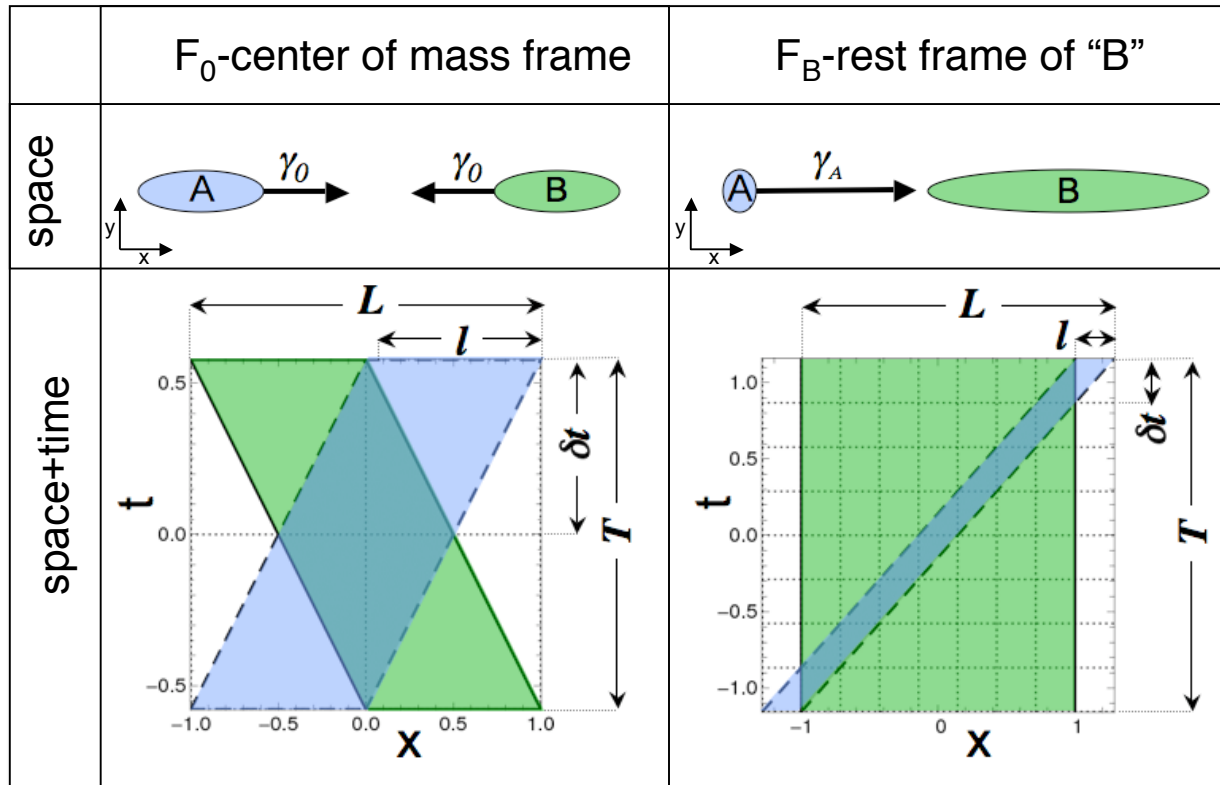
Proof of principle simulation:



- Fermilab: study of e-cloud in MI upgrade (K. Sonnad)
- ILC: study of e-cloud in positron damping ring wigglers (C. Celata)

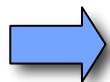
How can FSC compete with QS? Recent key observation: range of space and time scales is **not** a Lorentz invariant*

- **same** event (two objects crossing) in **two** frames



Consequences

- there exists an **optimum** frame which **minimizes** ranges,
- for **first-principle** simulations (PIC), **cost** $\propto T/\delta t \sim \gamma^2$ ($\propto L/l * T/\delta t \sim \gamma^4$ w/o moving window),



for large γ , potential savings are HUGE!

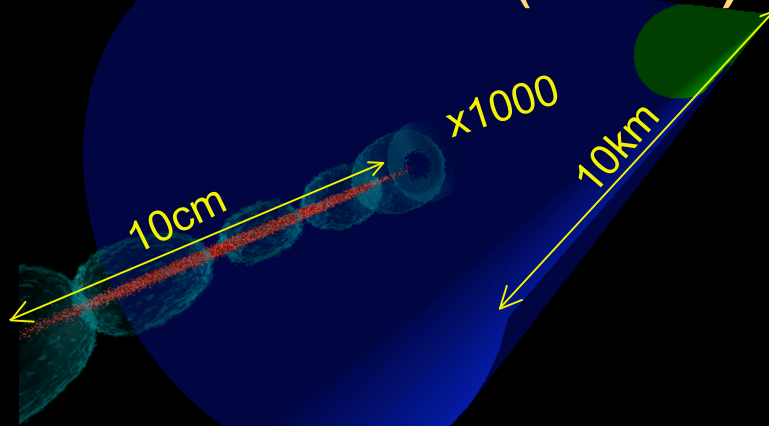
*J.-L. Vay, PRL 98, 130405 (2007)

A few systems which might benefit include...

In laboratory frame.

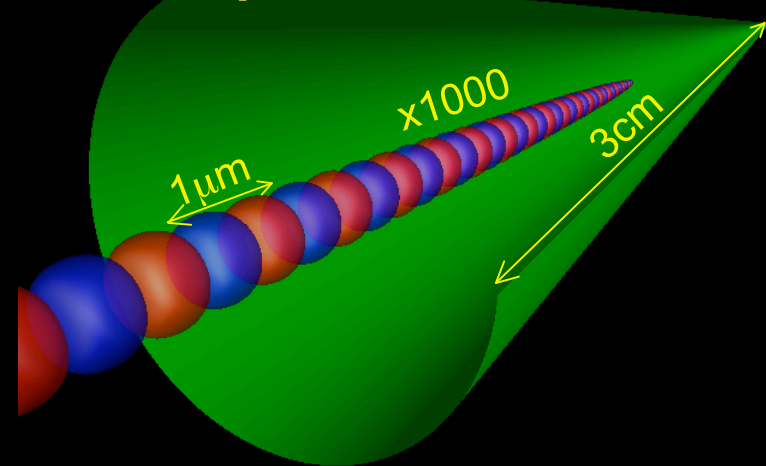
longitudinal scale
x1000/x1000000...
... so-called “**multiscale**” problems
= very challenging to model!
Use of approximations
(quasi-static, eikonal, ...).

HEP accelerators (e-cloud)



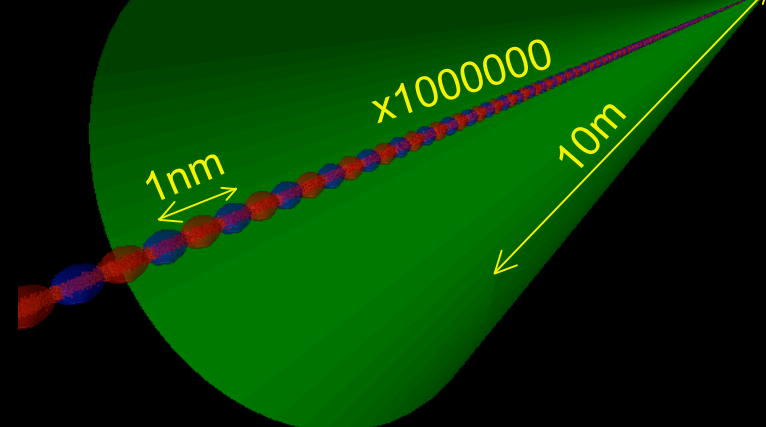
$$10\text{km}/10\text{cm} = 100,000.$$

Laser-plasma acceleration



$$3\text{cm}/1\mu\text{m} = 30,000.$$

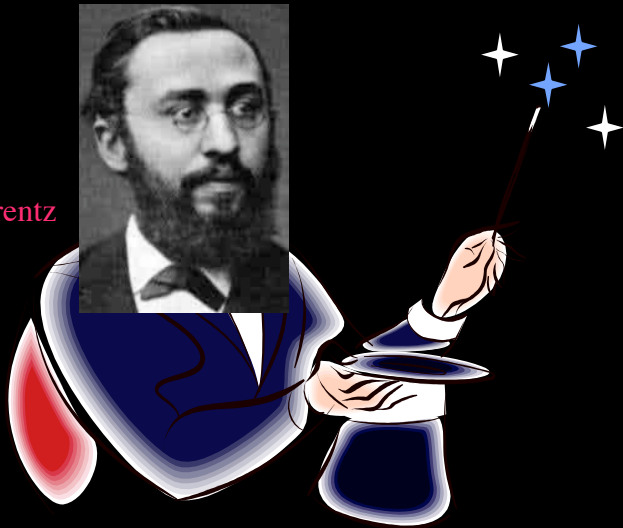
Free electron lasers



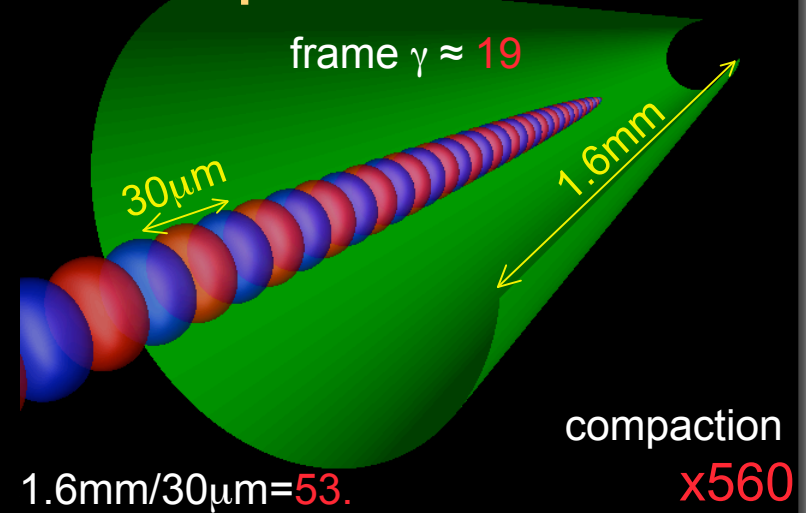
$$10\text{m}/1\text{nm} = 10,000,000,000.$$

Lorentz transformation => large level of compaction of scales

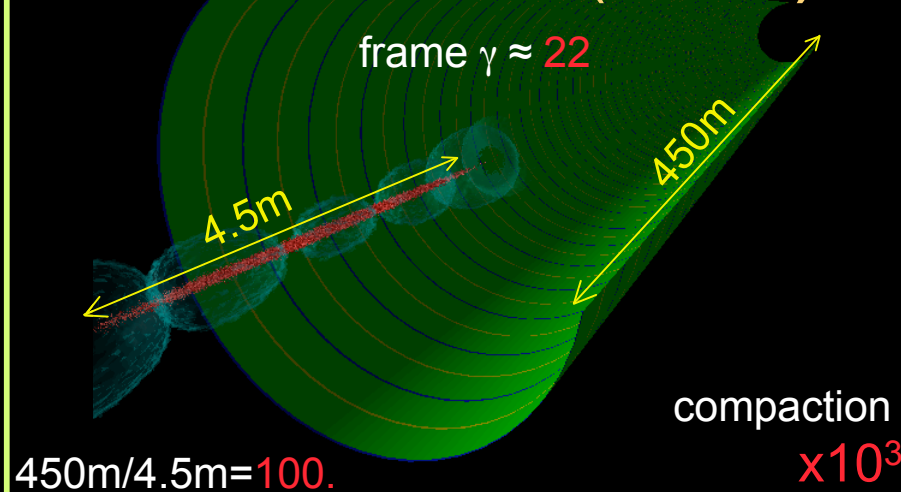
Hendrik Lorentz



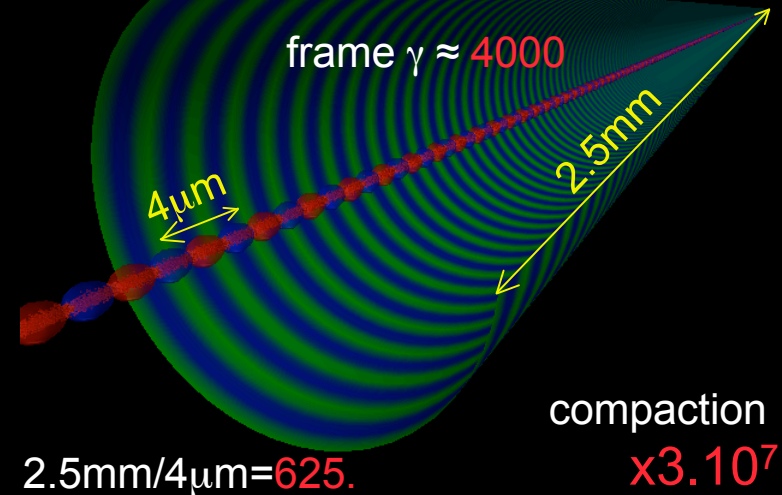
Laser-plasma acceleration



HEP accelerators (e-cloud)



Free electron lasers

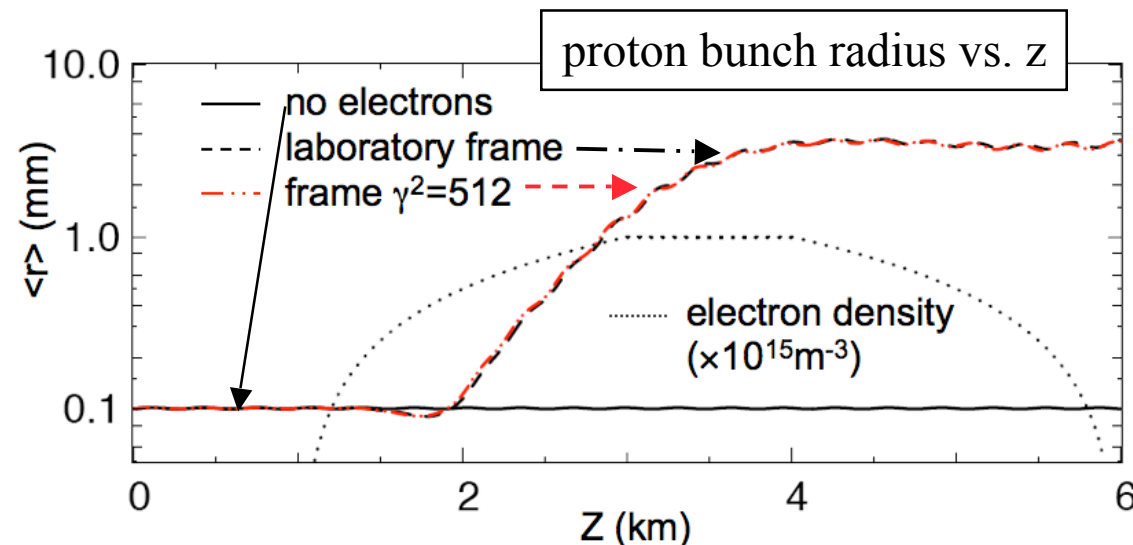
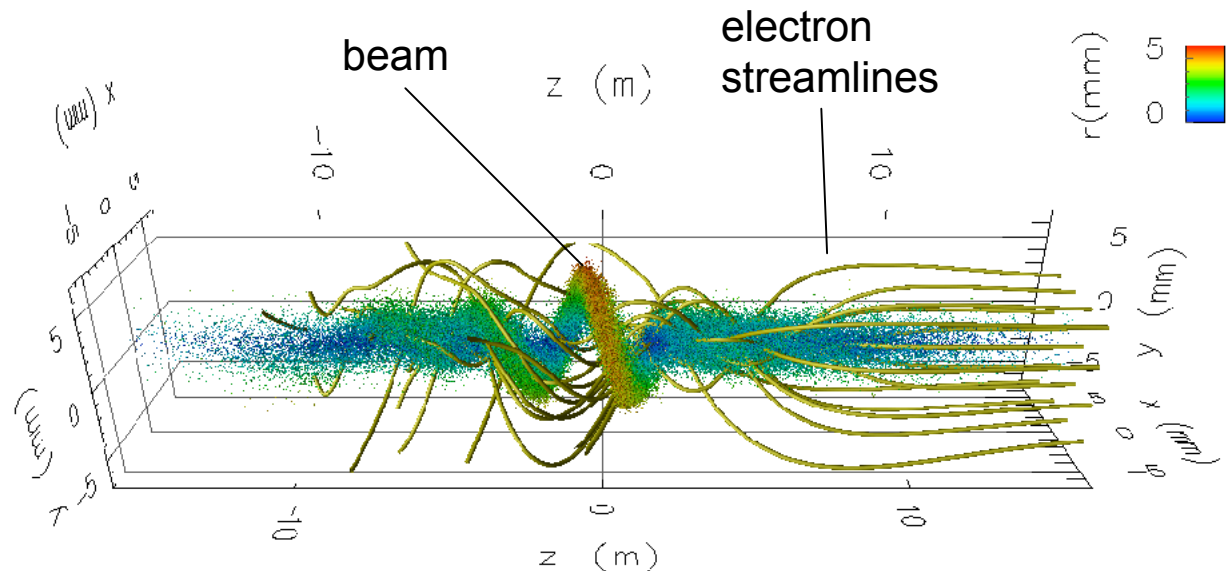


Boosted frame calculation sample

proton bunch through a given e^- cloud*

This is a proof-of-principle computation:
hose instability of a
proton bunch

Proton energy: $\gamma=500$ in Lab
• L= 5 km, continuous focusing



CPU time:

- lab frame: >2 weeks
- frame with $\gamma^2=512$: <30 min

Speedup x1000

*J.-L. Vay, PRL 98, 130405 (2007)

Summary

- **WARP/POSINST code suite developed for HIF e-cloud studies**
 - Parallel 3-D AMR-PIC code with accelerator lattice follows beam **self-consistently** with gas/electron generation and evolution,
- **Benchmarked against HCX**
 - **highly instrumented** section dedicated to e-cloud studies,
- **Being applied outside HIF/HEDP, to HEP accelerators**
 - found that cost of self-consistent calculation is greatly reduced in **Lorentz boosted frame (with $\gamma \gg 1$)**, thanks to relativistic contraction/dilatation bridging space/time scales disparities,
 - 1000x speedup demonstrated on proof-of-principle case,
 - will apply to LHC, Fermilab MI, ILC.